Session 4, P5

Rare-Earth Plasma EUV Source at 6.7 nm for Future Lithography

Takeshi Higashiguchi[1,2]

Takamitsu Otsuka[1], Noboru Yugami[1,2], Deirdre Kilbane[3], Thomas Cummins[3], Colm O’Gorman[3], Tony Donnelly[3], Padraig Dunne[3], Gerry O'Sullivan[3], Weihua Jiang[4], and Akira Endo[5]

[1]Utsunomiya University
[2]Japan Science and Technology Agency
[3]University College Dublin
[4]Nagaoka University of Technology
[5]Waseda University

2011 International Workshop on EUV Lithography
Makena Beach Golf Resort , Maui, Hawaii, USA
Wednesday, June15, 2011

Why 6.X nm EUV source?

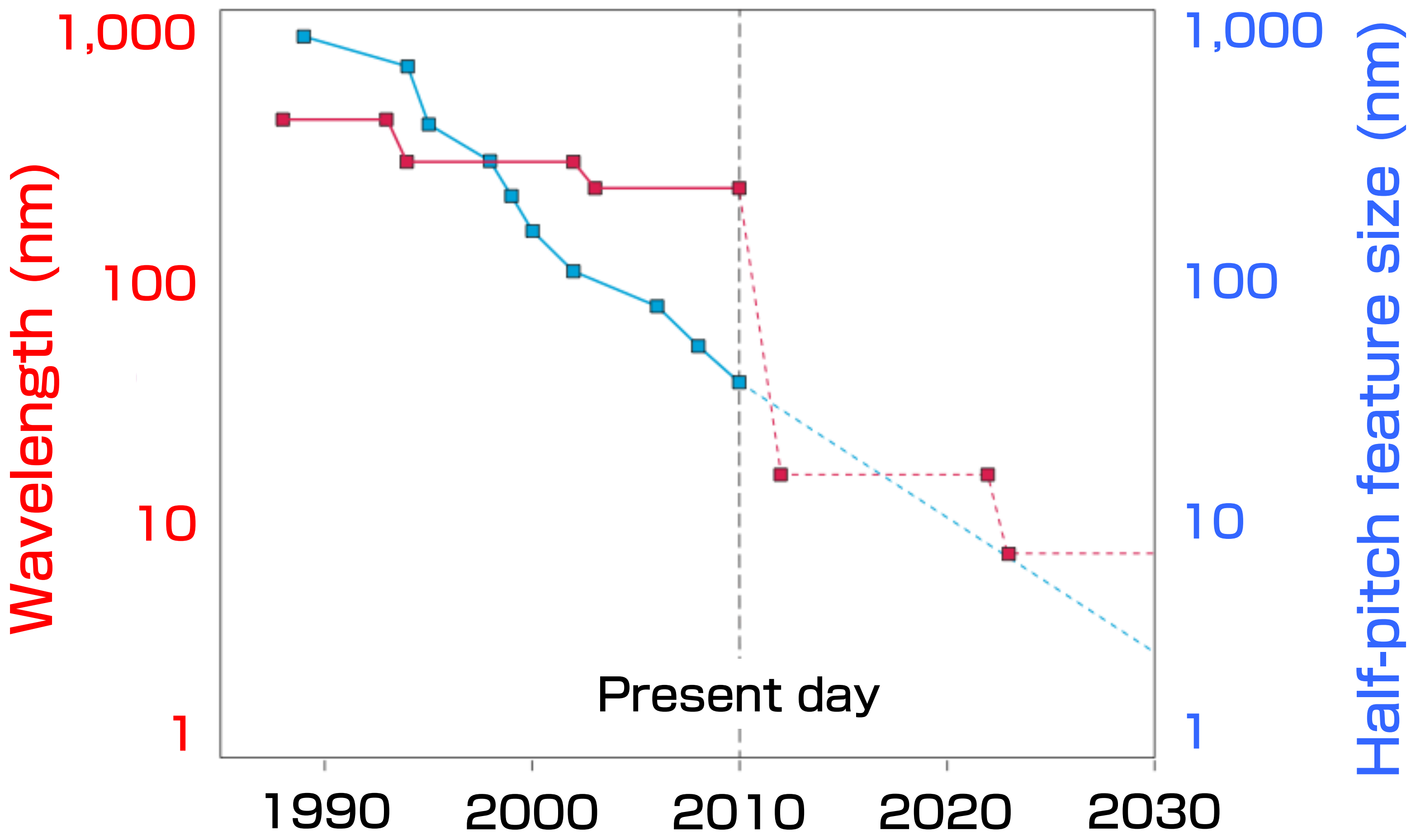
Beyond EUV (BEUV) source

From ASML presentation shows as follows:

(1) extensive (beyond 8 nm@~2017)
(2) **6.X nm choice: Best transmission & Easier Manufacturing**
(3) Source: New fuel is needed
(4) R ~ 80% (cal), R ~ 40% (exp)@La/B_4C MLM
(5) ***Total throughput for 6.7 nm & 13.5 nm is comparable!!!***

Why 6.X nm EUV source?

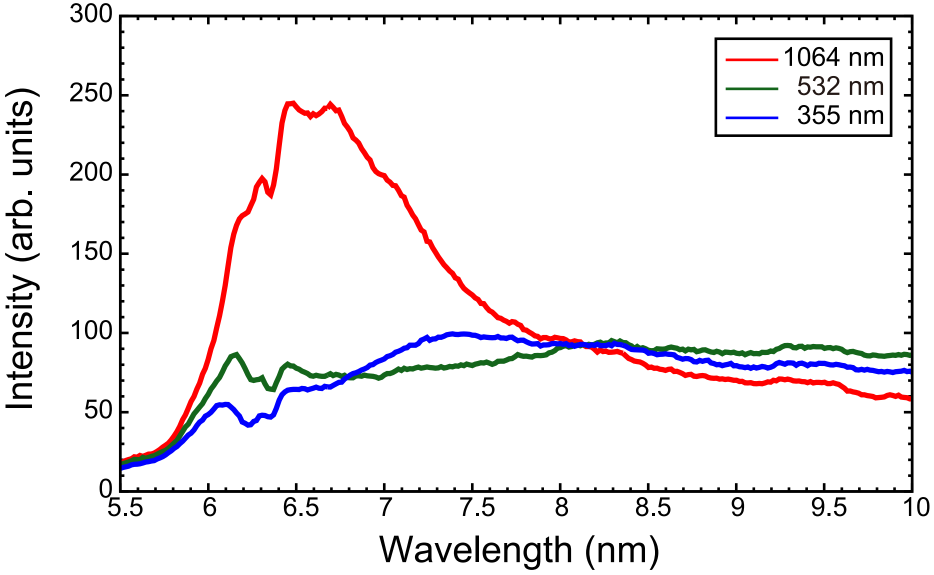
Beyond EUV (BEUV) source

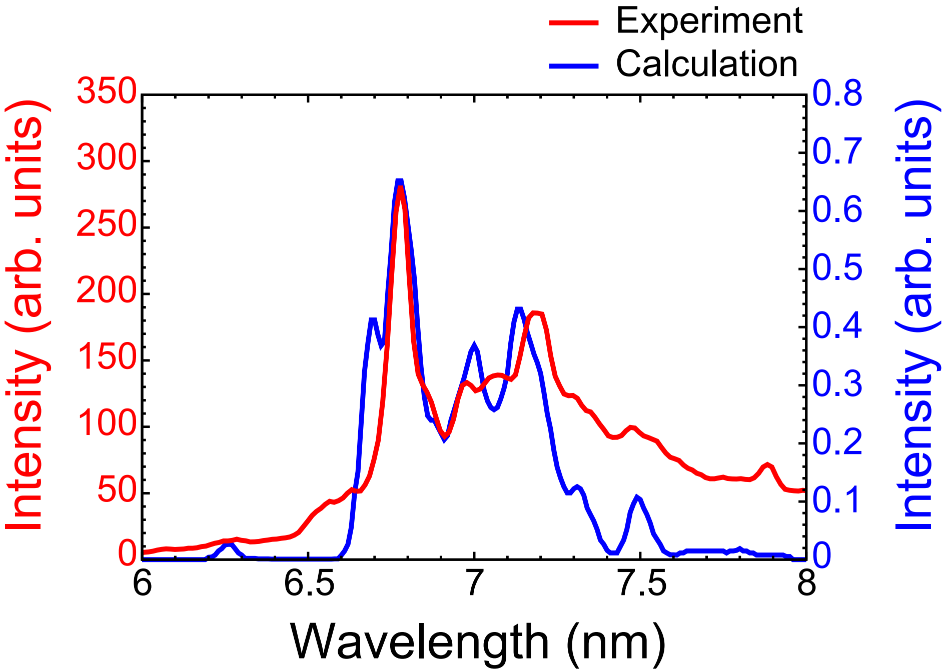


G. Tallents et al., NATURE PHOTONICS, **4**, 809 (2010).

What's new
for high power and high CE

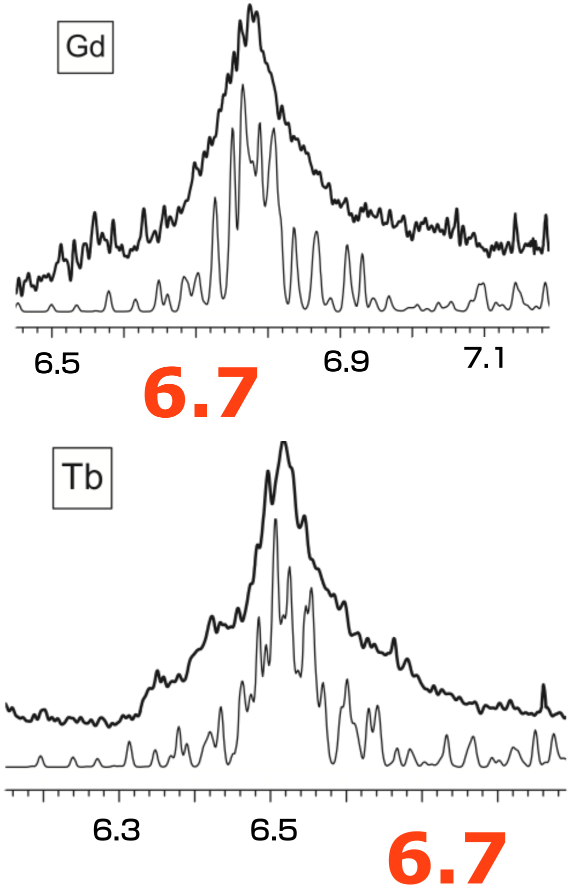
- ■ Laser color dependence
- ■ Resonant line appearance in low-density plasma
- ■ Enhancement condition of the 6.7-nm emission



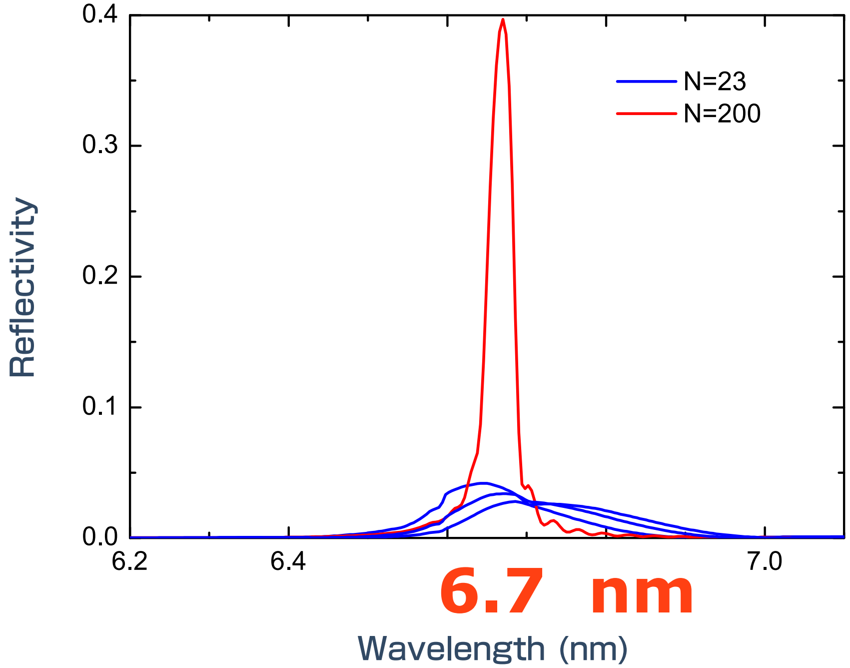


Introduction…
from previous spectral reports

6.7 nm: Gd, Tb plasmas



Mo/B$_4$C mirror



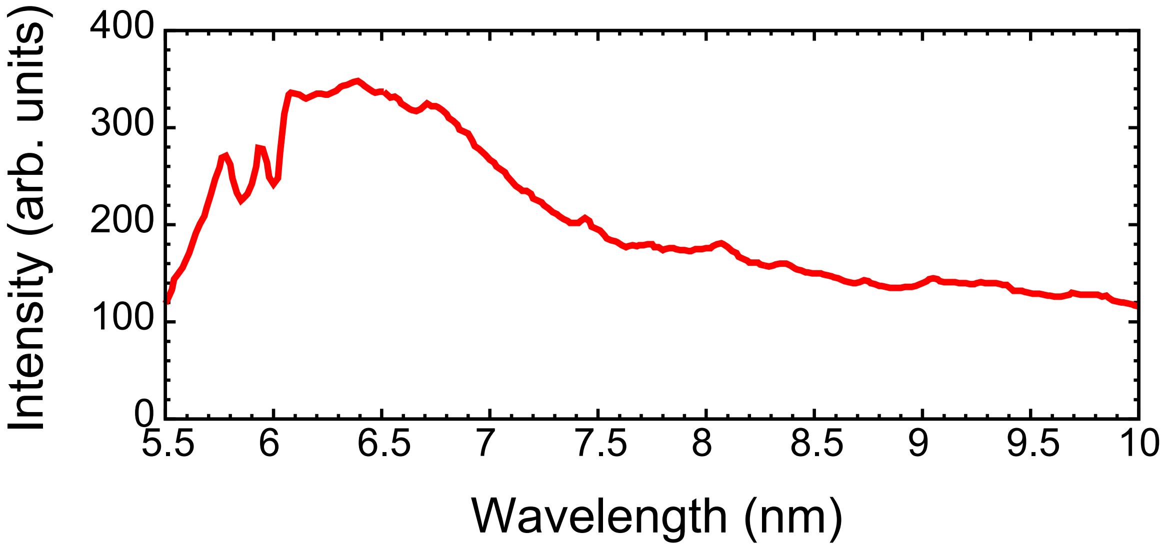
S. S. Churilov *et al.*,Phys. Scr. **80**, 045303 (2009).

Previous & recent observations

We observed continuum due to satellite lines

for absorption spectroscopy

for high power source by us



G. O'Sullivan & P. K. Carroll, JOSA **71**, 227 (1981).
T. Otsuka *et al*., APL **97**, 111503 (2010).

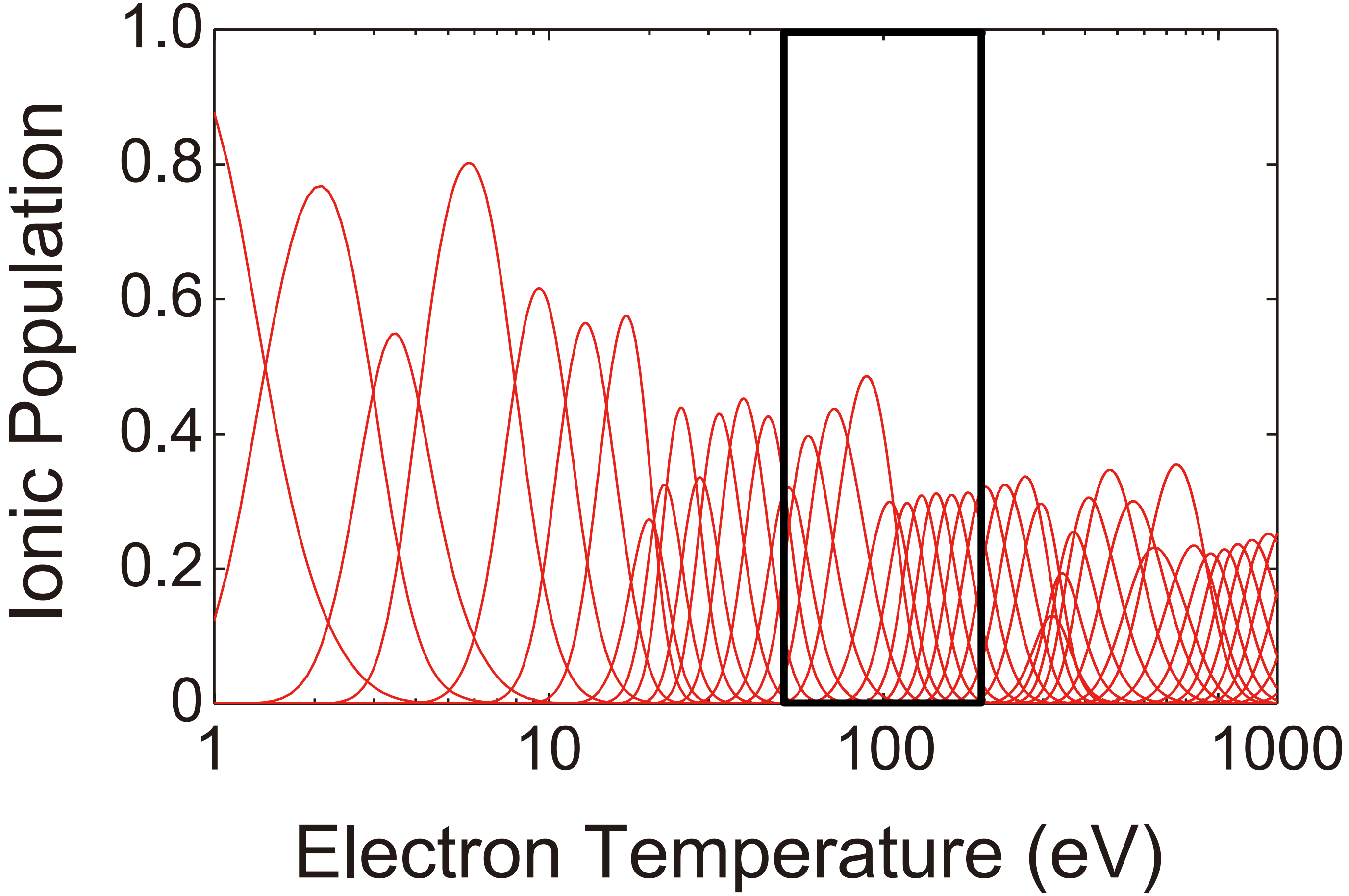
Objective

We demonstrate the efficient BEUV source

at 6.7 nm by rare-earth (Gd) LPP and DPP .

Ionic population of Gd ions

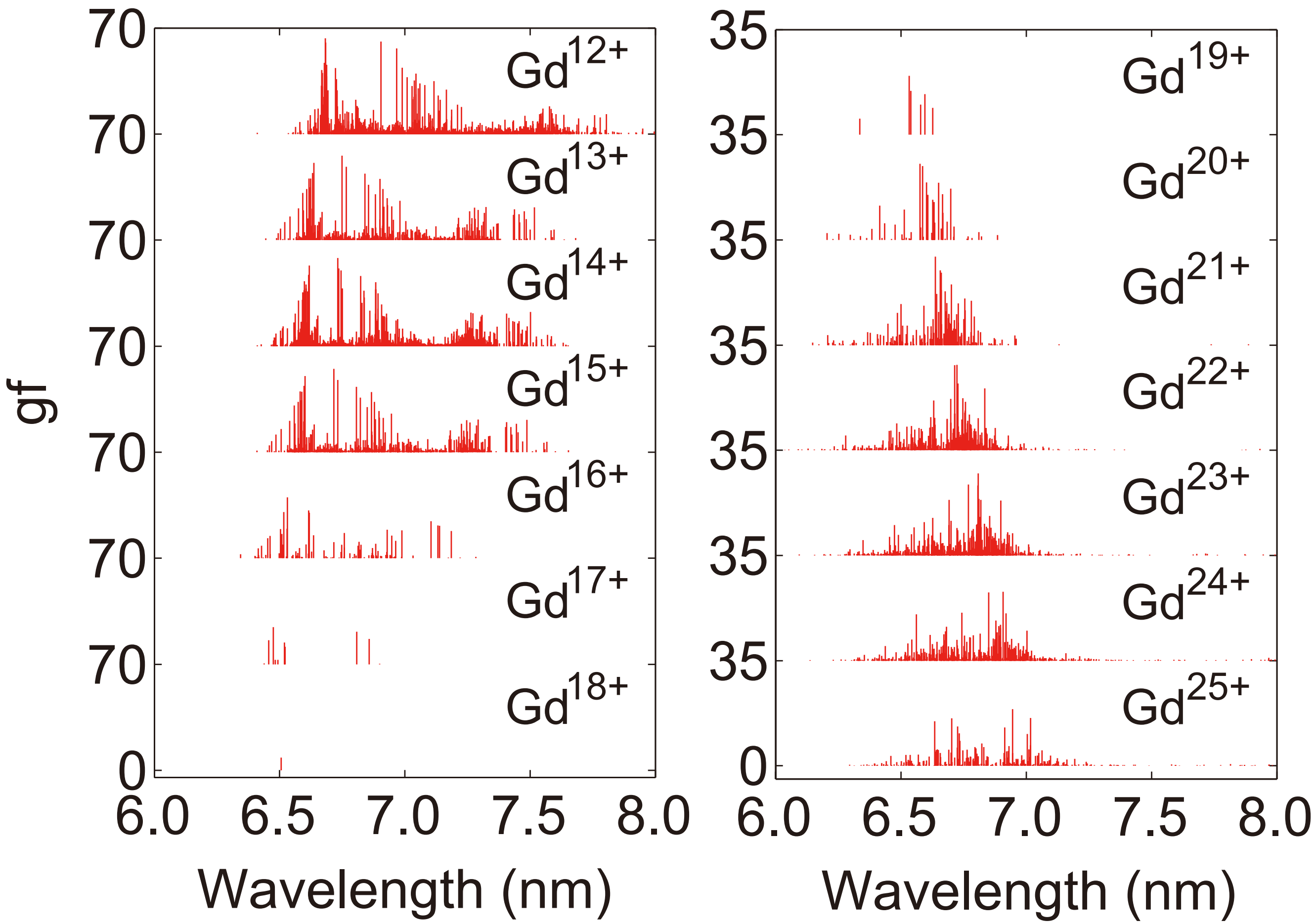
We should produce 50-200 eV plasma.



T. Otsuka *et al.*, APL **97**, 111503 (2010).

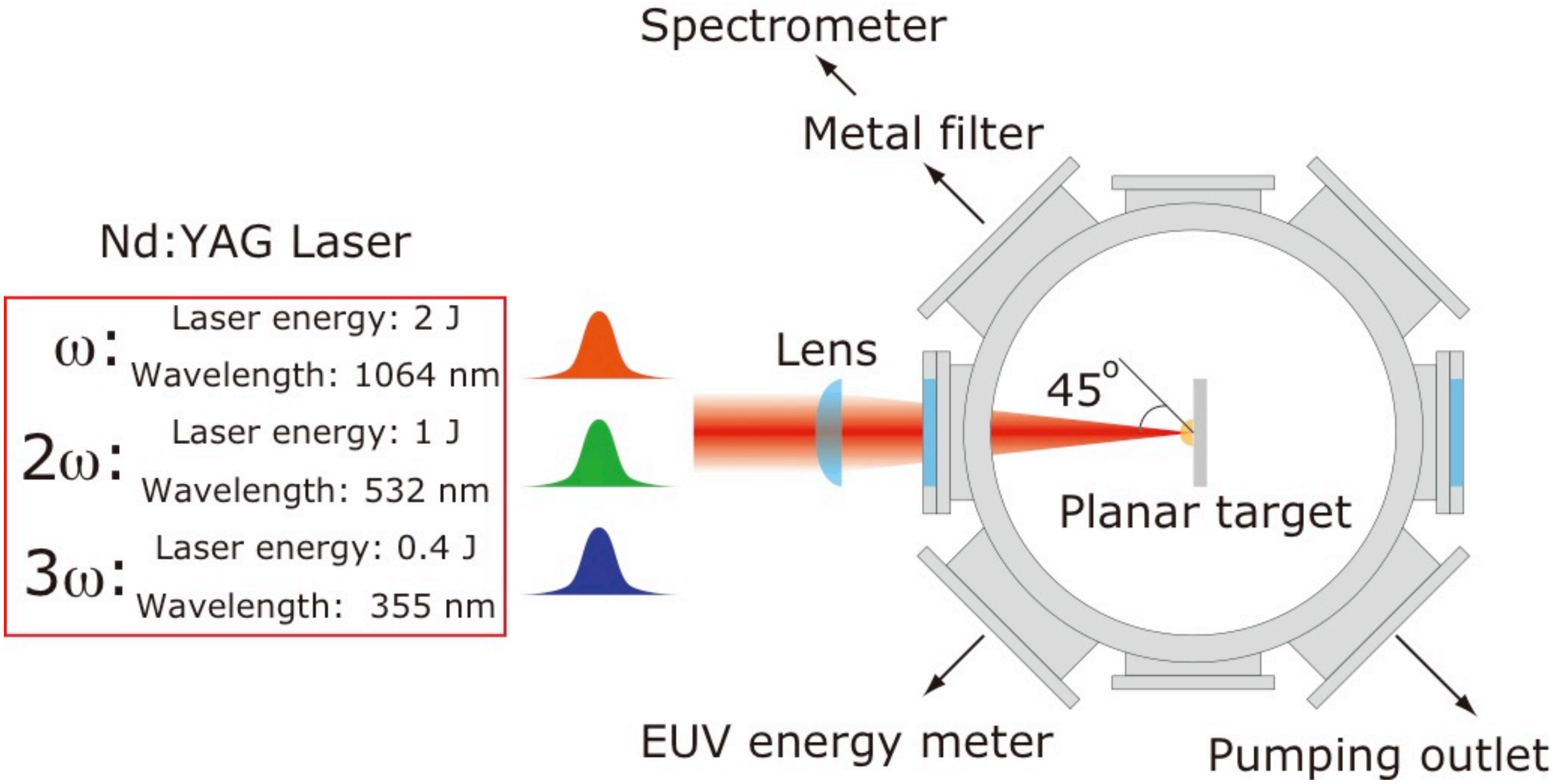
gf spectra of Gd ions

We confirm the UTA resonant lines around 6.7 nm

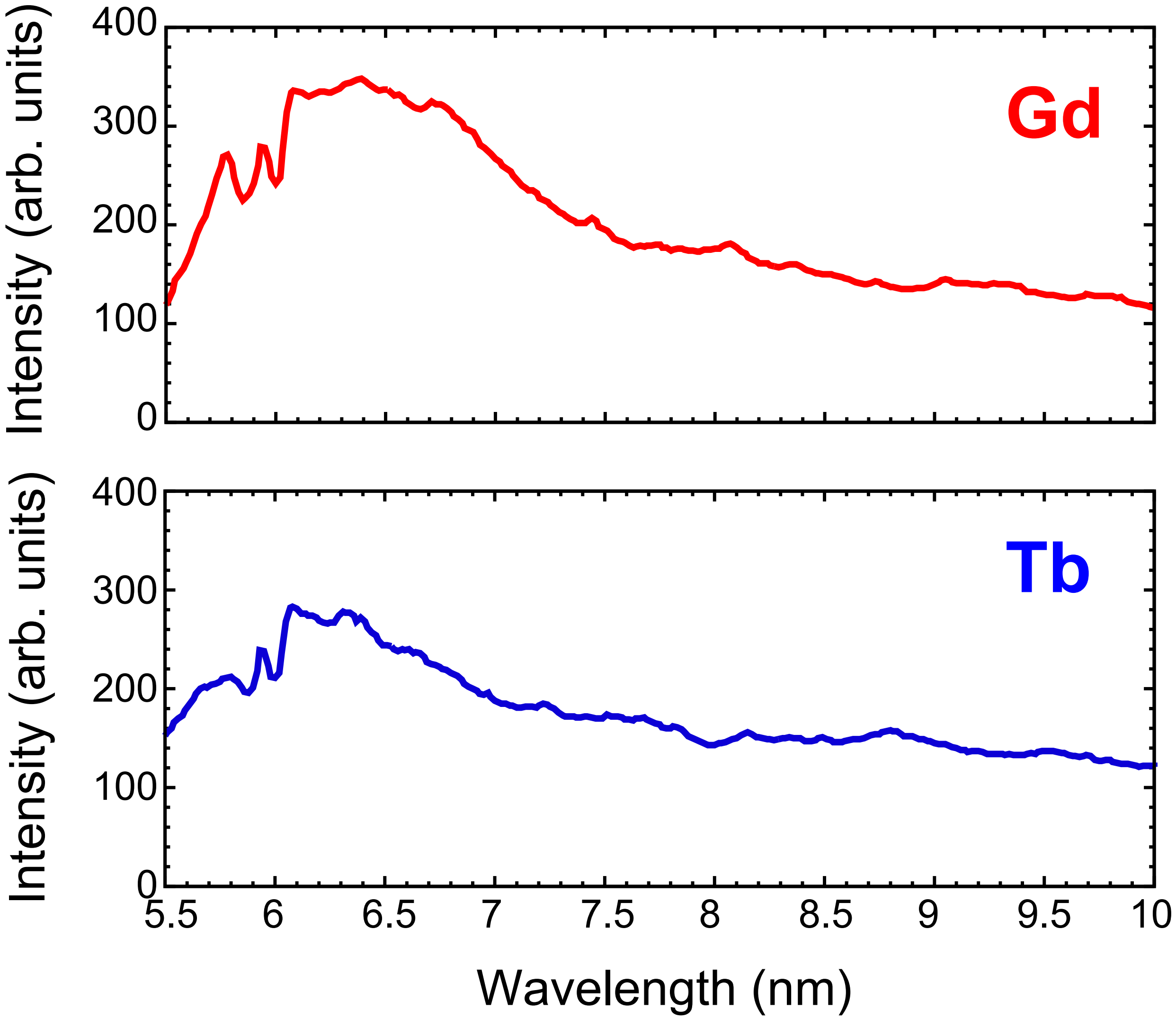


T. Otsuka *et al*., APL **97**, 111503 (2010).

Experimental setup

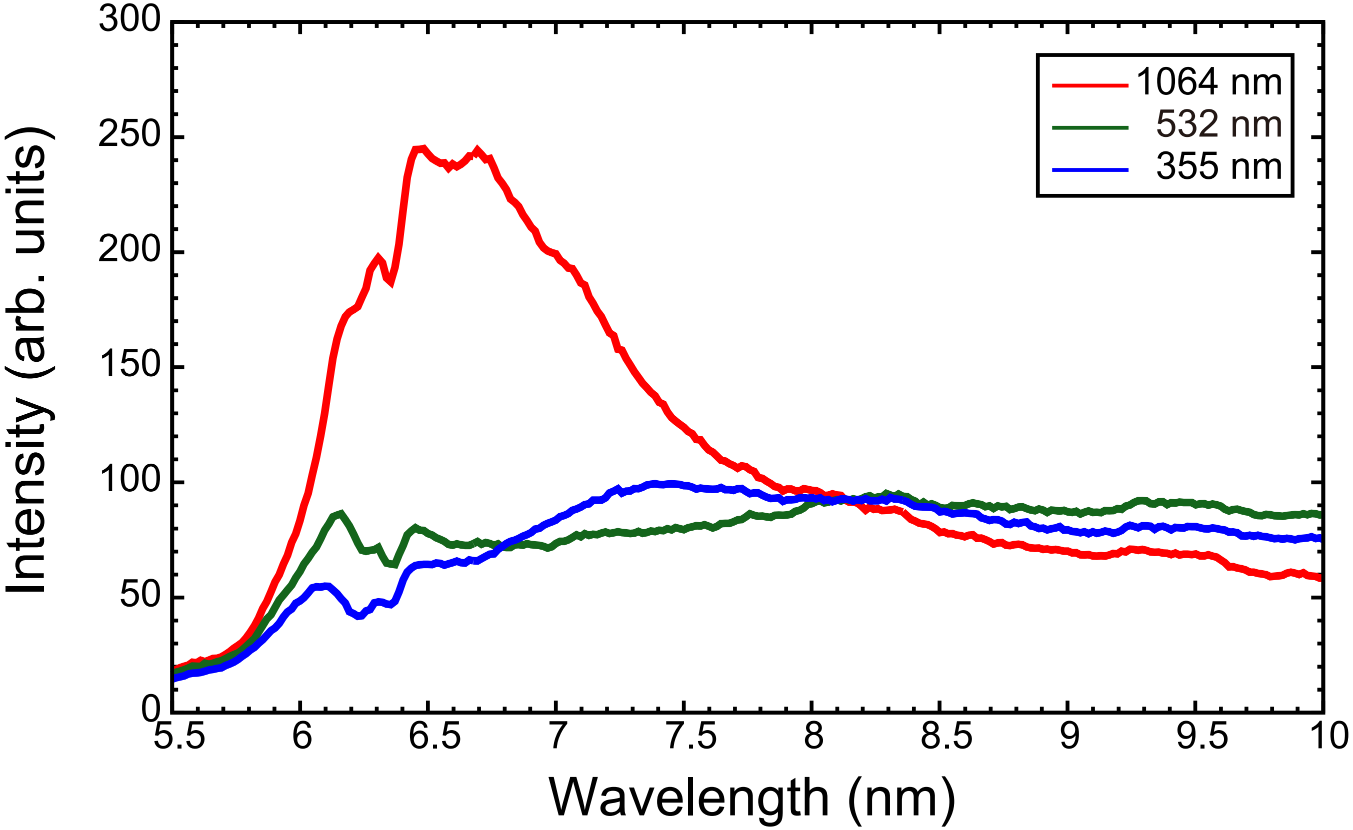


Spectra from Gd & Tb plasmas



Laser wavelength dependence

- Spot diameter: 50 um (FWHM)
- Laser energy: 320 mJ
- Laser intensity: 1.6 x 10^{12} W/cm^2



EUV CEs
(in 2% BW)

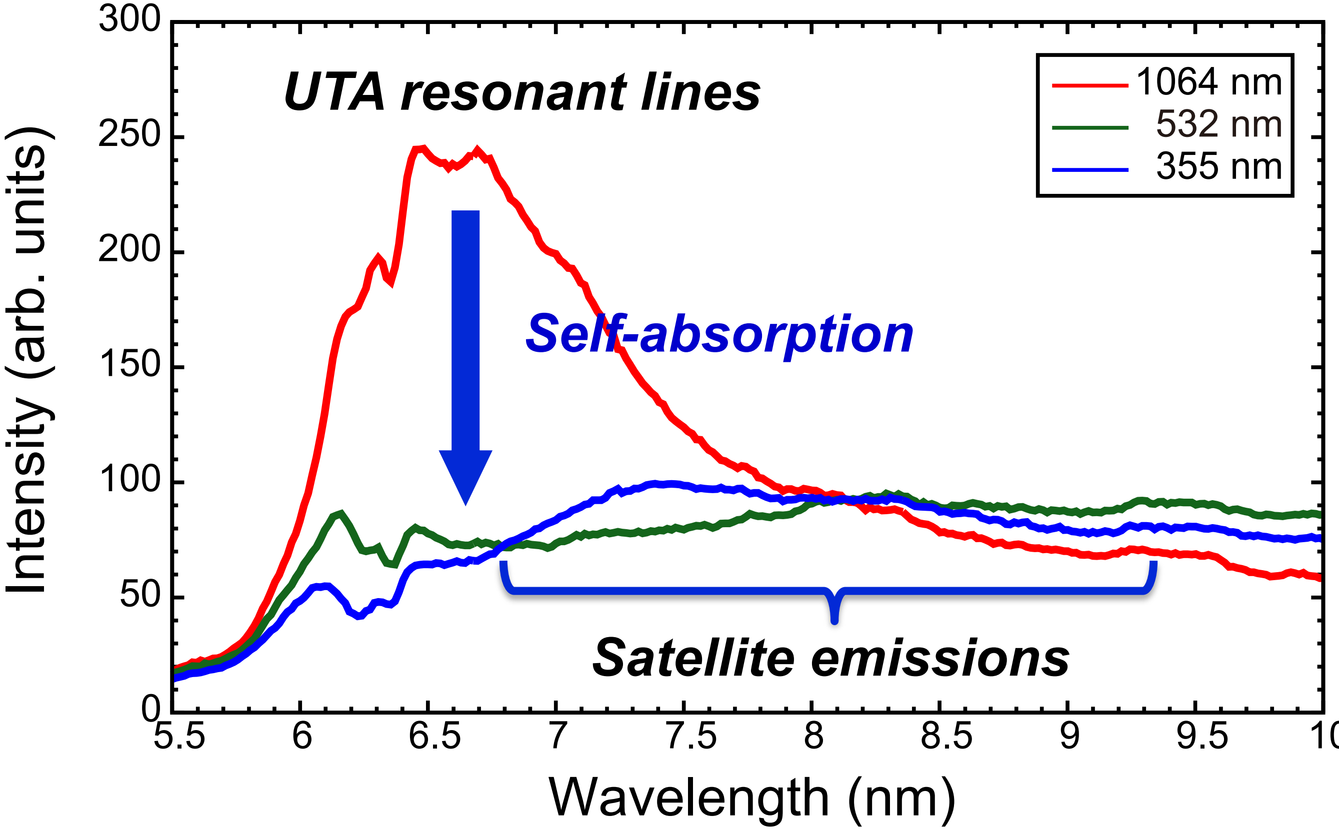
1064 nm: 1.1%

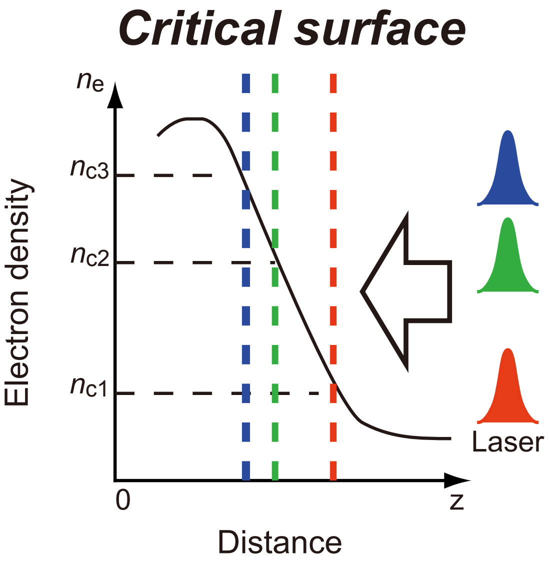
532 nm: 0.7%

355 nm: 0.5%

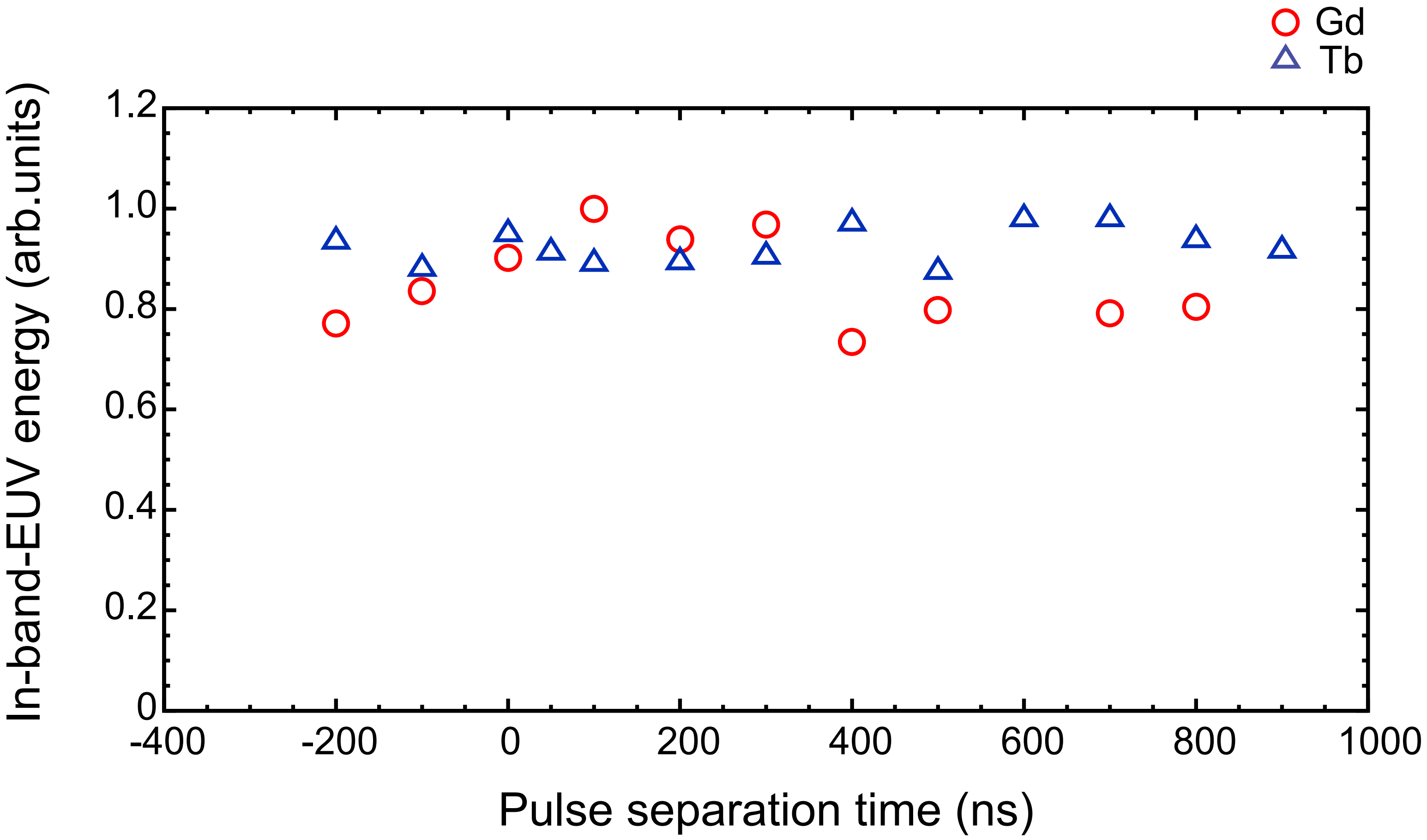
Laser wavelength dependence

- ■ Spot diameter: 50 um (FWHM)
- ■ Laser energy: 320 mJ
- ■ Laser intensity: 1.6 x 10^{12} W/cm^2





Dual laser pulse irradiation



Trade off 1

Effective ions vs self-absorption

Electron (ion) density decreases,

but ***absorption length increases***.

For large opacity material (high-*Z*), such as Xe & Sn

Electron density decreased: absorption effect decreased
Density gradient increased: absorption effect increased

For small opacity material (low-*Z*),
such as Li & low initial density target

Electron density decreased: absorption effect more decreased
Density gradient increased: large volume effect increased

Physical summary for high-Z plasmas

from 13.5-nm Sn plasmas

Low density plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

Long wavelength (low critical density): CO_2 laser@10^{19} /cc

Short laser pulse duration: ~1-2 ns@YAG laser (1064 nm)

Low density targets

Discharge plasmas (low density plasmas)

Effective dual pulse scheme

We require the use of:

low initial density target & DPP

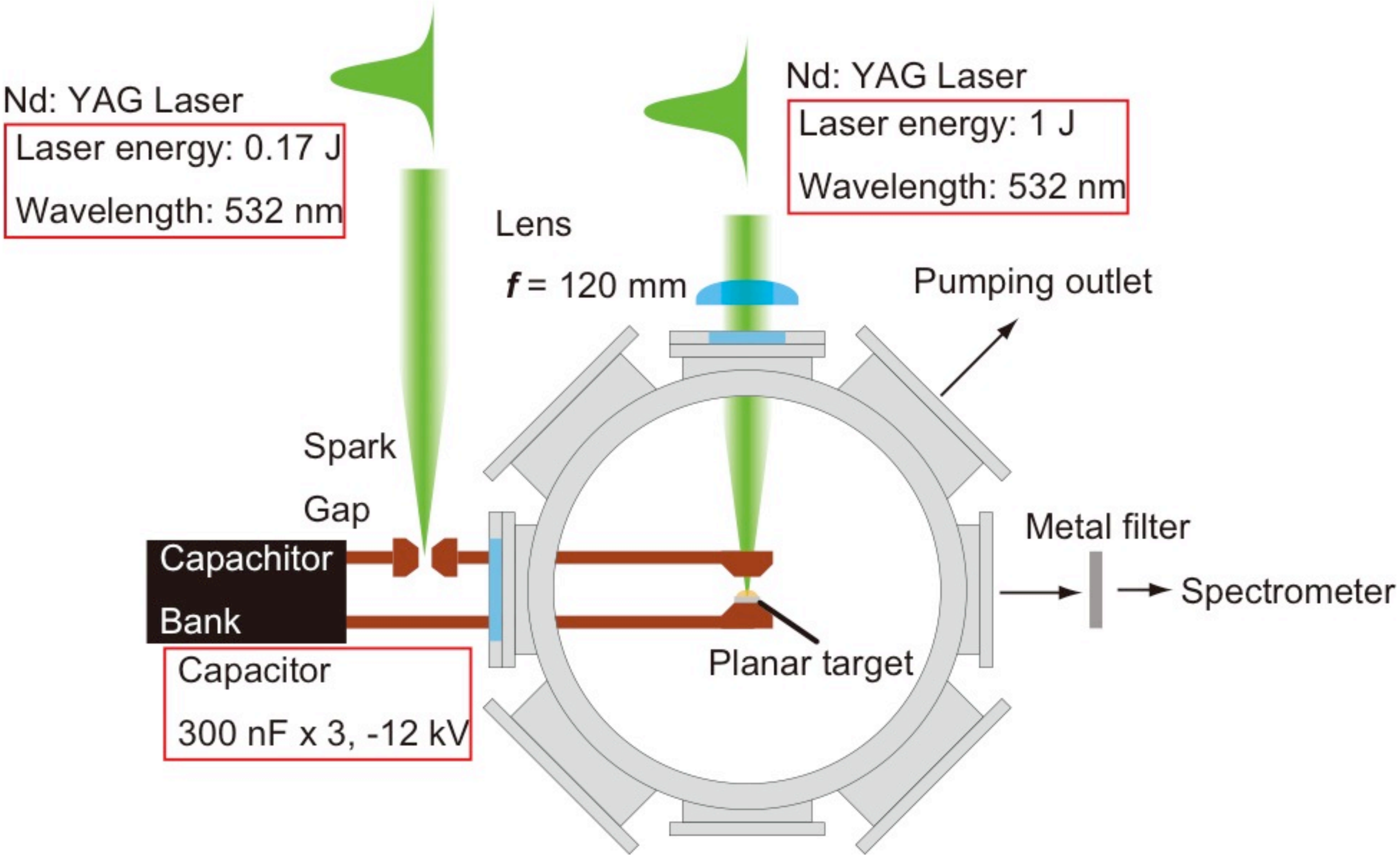
or

longer laser wavelength laser

in the **self-absorption effect suppression** point of view.

Discharge experiments

To reduce the satellite lines for low density plasma



Nd: YAG Laser

Laser energy: 0.17 J

Wavelength: 532 nm

Nd: YAG Laser

Laser energy: 1 J

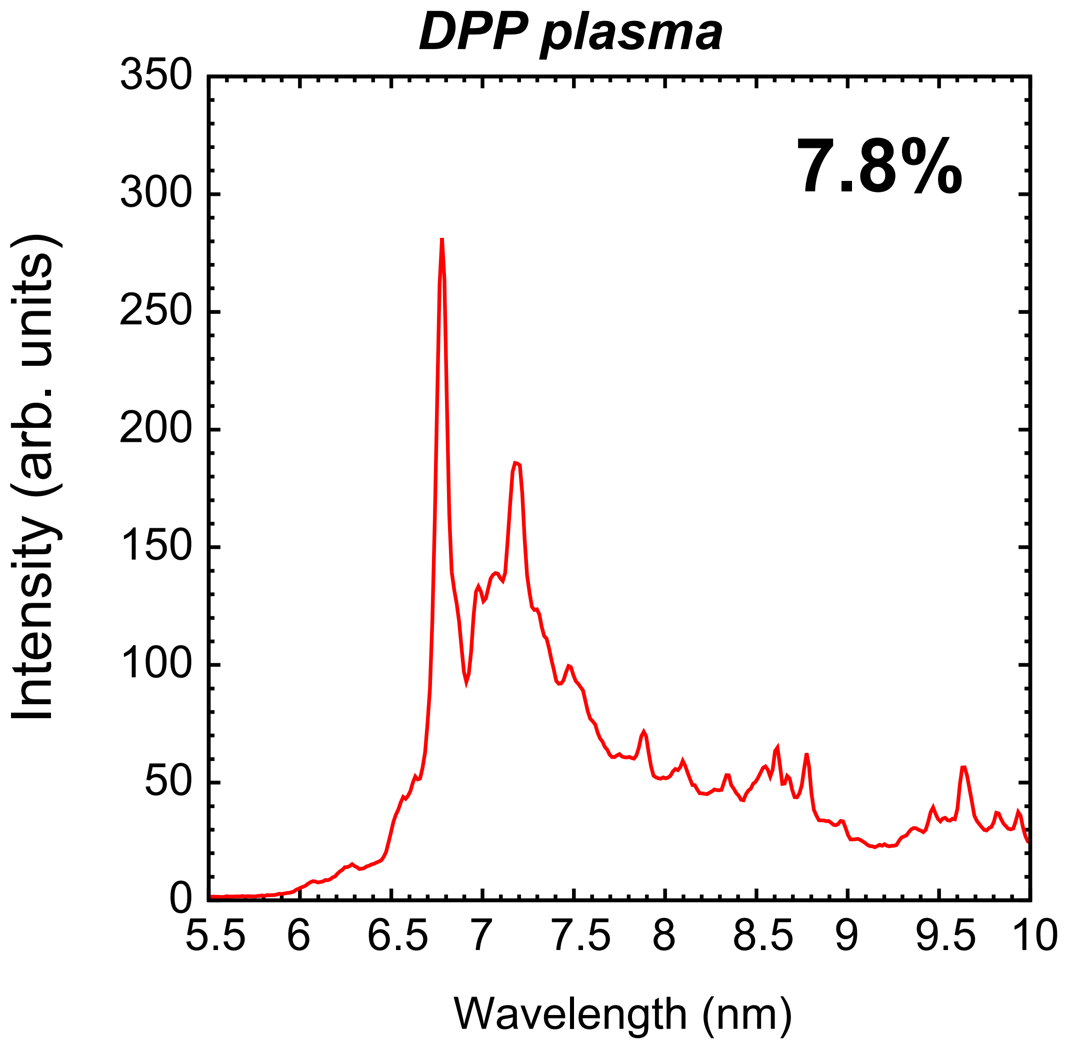
Wavelength: 532 nm

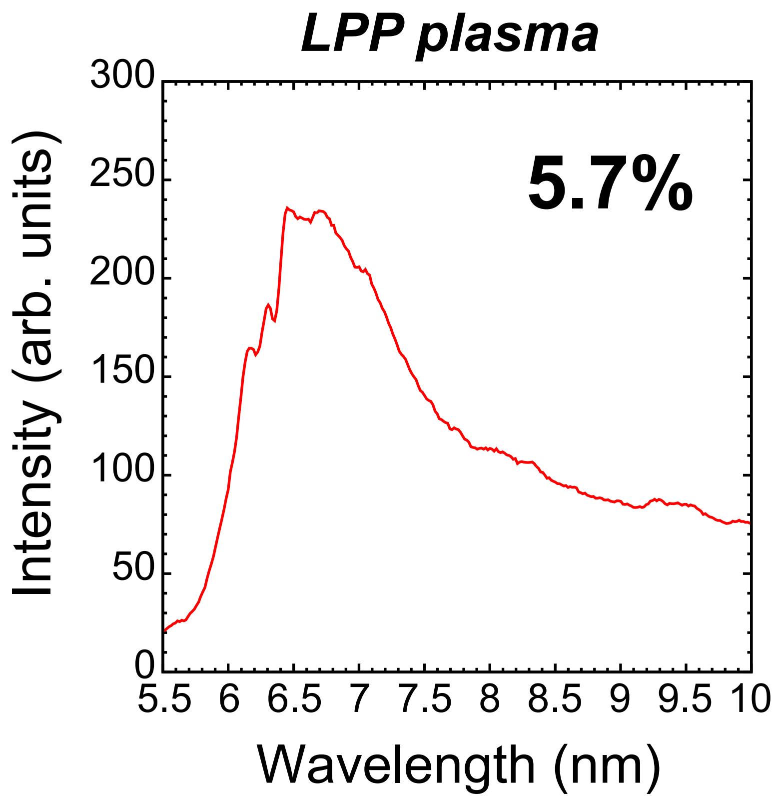
Capacitor

300 nF x 3, -12 kV

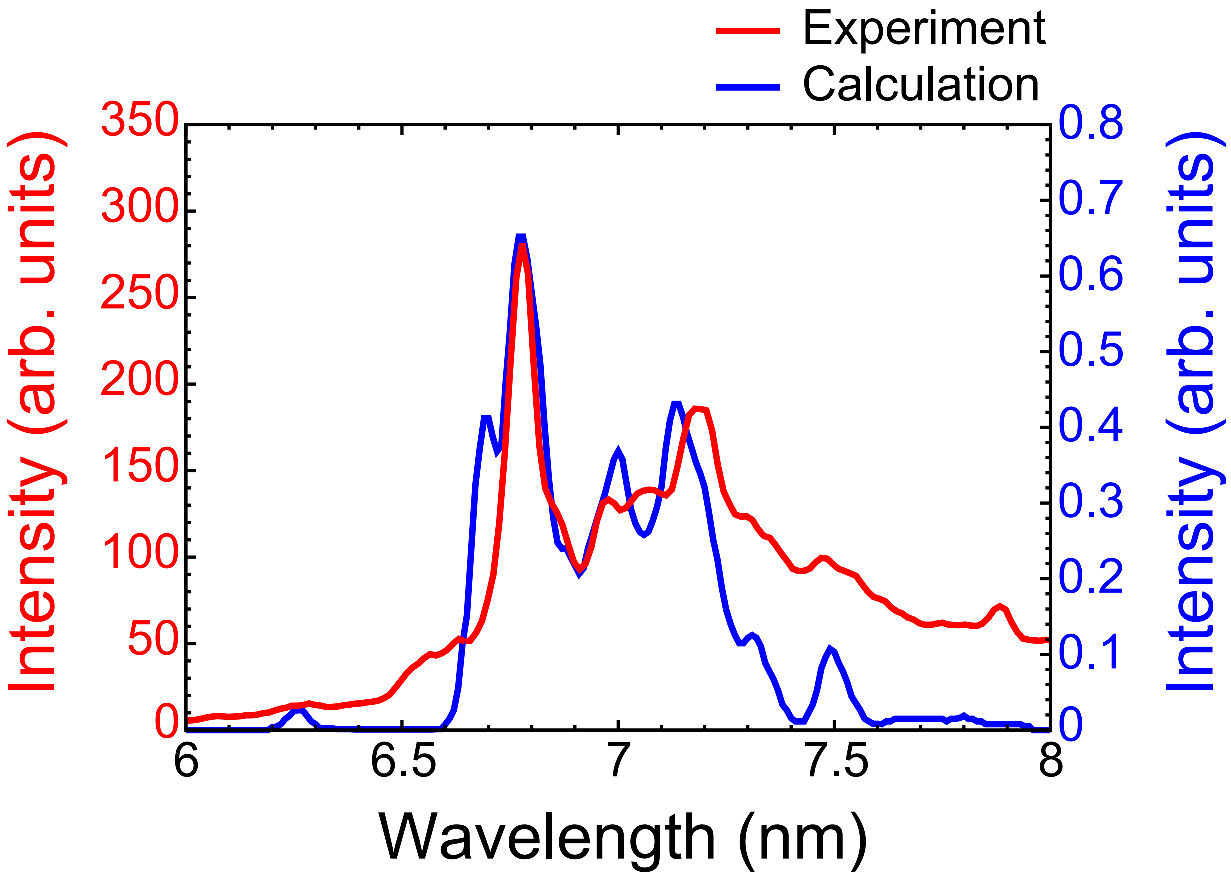
Discharge experiments

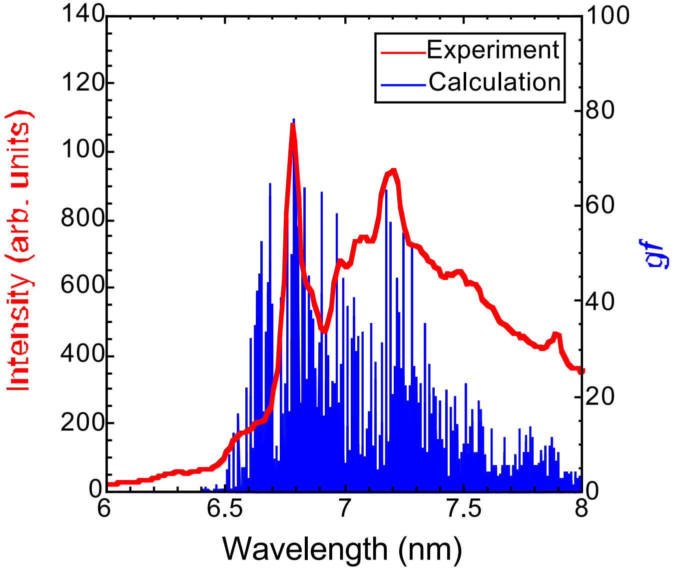
To reduce the satellite lines for low density plasma





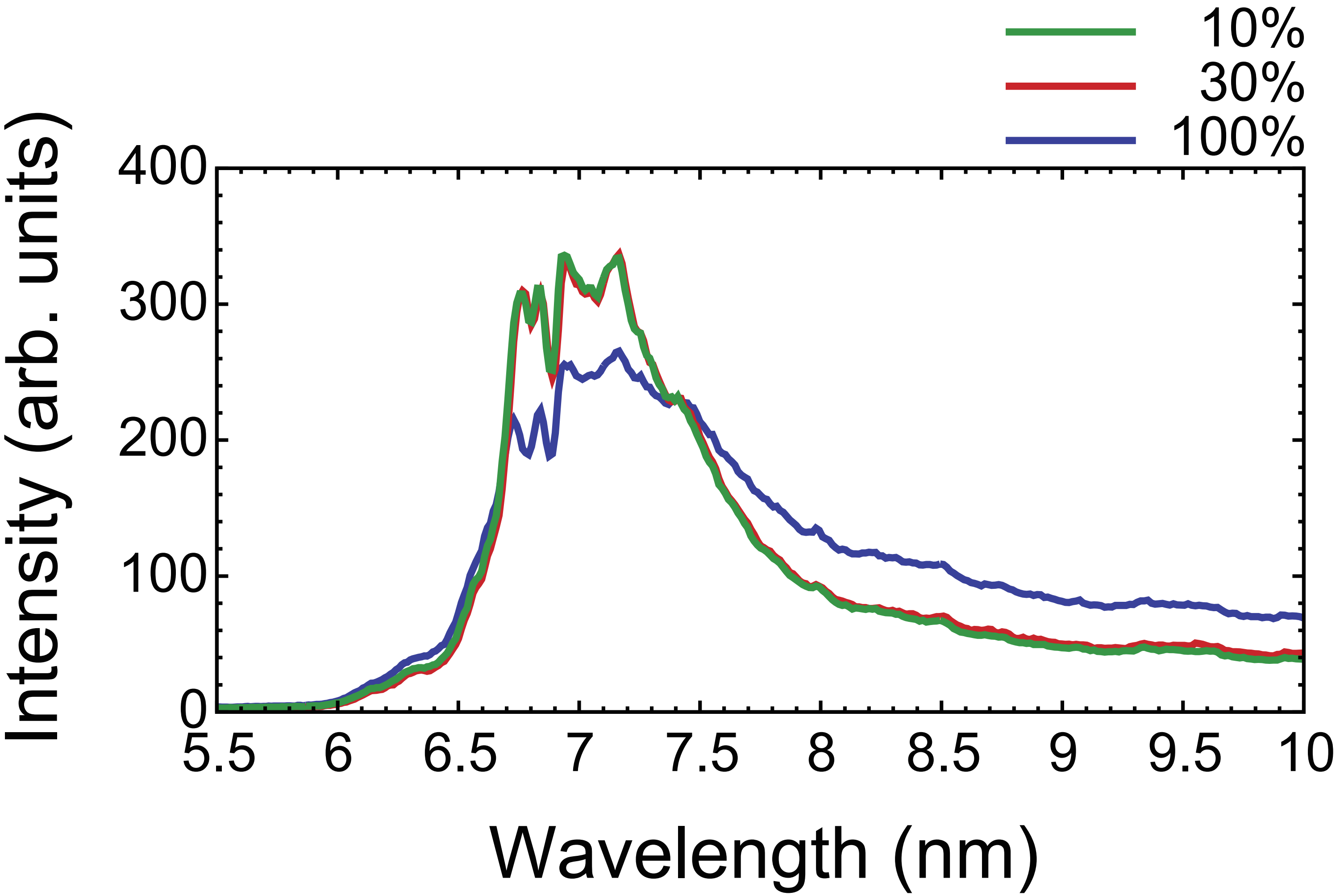
Low density plasma by DPP



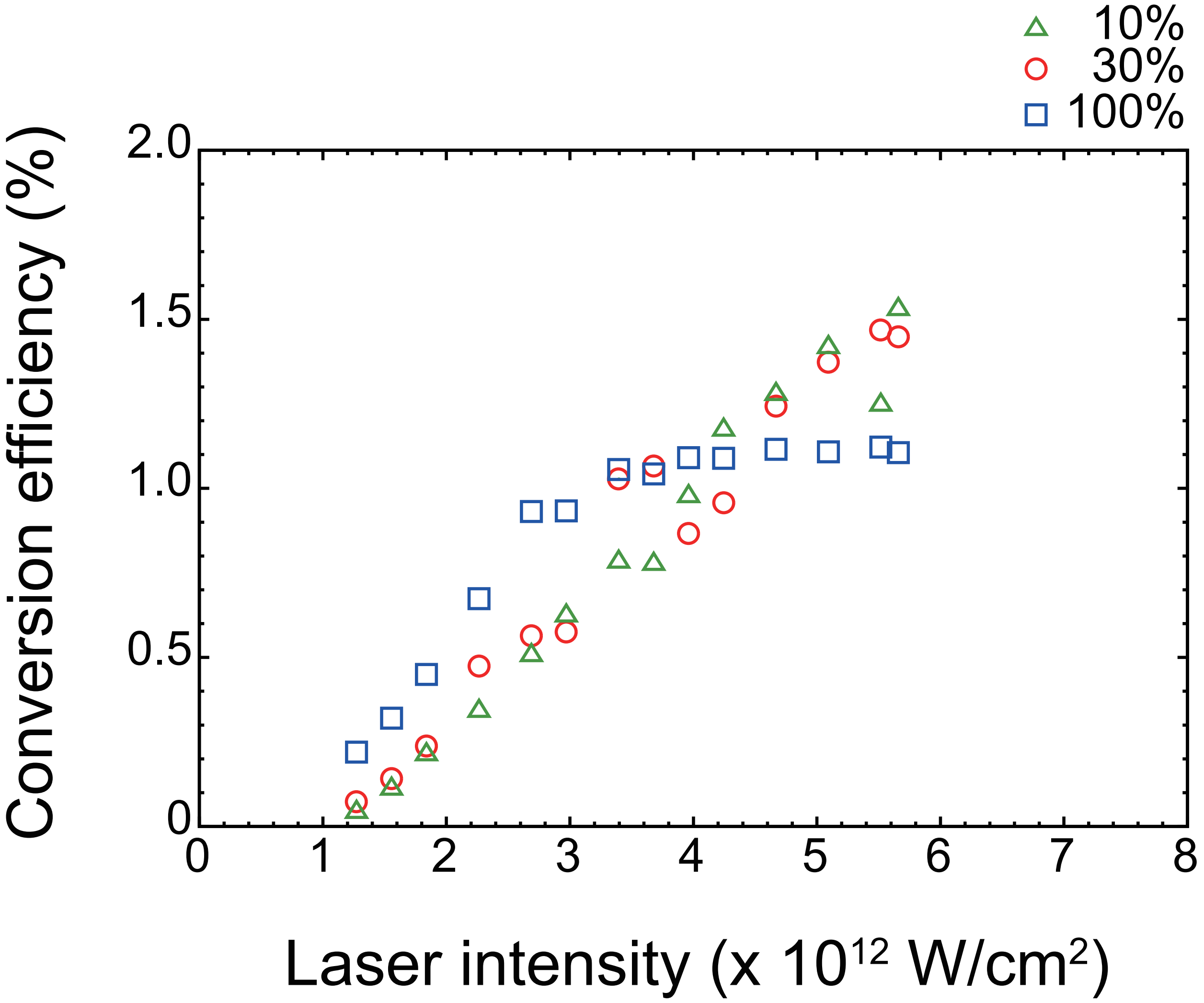


***calculated by Bowen Li &
Gerry O’Sullivan
(UCD)***

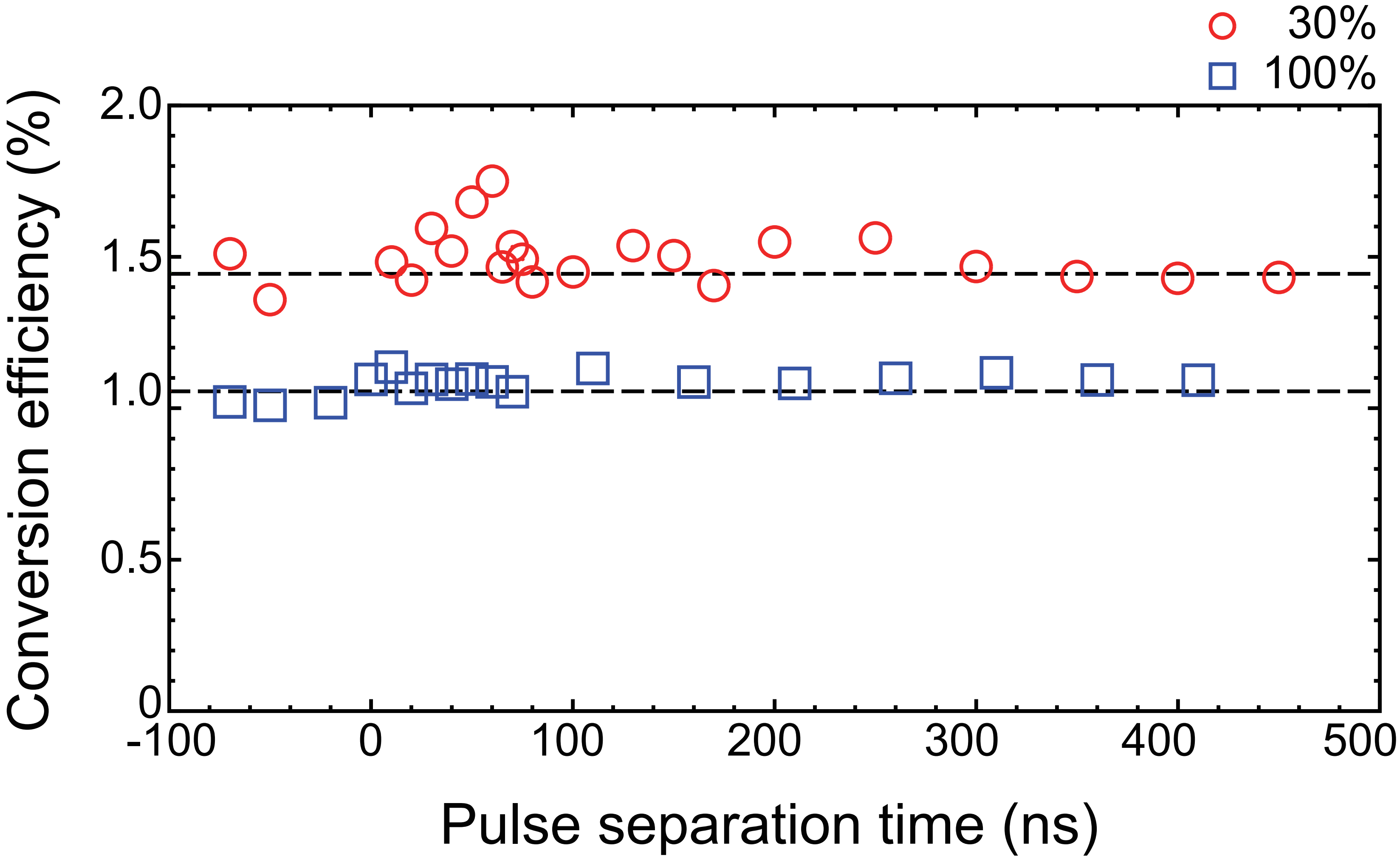
Low density plasma by use of low-initial density targets



EUV CEs by use of low-initial density targets



Enhancement of EUV CE by use of dual laser pulse technique



Question, problem, and definition…

- CO_2 laser-produced plasma behavior?
- High temperature (30-50 eV to 50-150 eV):
  high energy particle generation
- CE bandwidth (2% to less than 0.1%?)
- Regenerative target supply method
  (melting point: 1313 ^{O}C)

Summary

We have demonstrated the efficient EUV source around 6.7 nm using Gd & Tb (rare-earth).

- Spectral behavior at different laser wavelength
- Low density target to ***suppress the self-absorption*** in plasma
- Conversion efficiency: **~ 1.8%** before optimizing parameters

- Question, problem, and definition